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## H I Recycling: Formation of Tidal Dwarf Galaxies

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### Abstract.

Galactic collisions trigger a number of phenomena, such as transportation inward of gas from distances of up to kiloparsecs from the center of a galaxy to the nuclear region, fuelling a central starburst or nuclear activity. The inverse process, the ejection of material into the intergalactic medium by tidal forces, is another important aspect and can be studied especially well through detailed H I observations of interacting systems which have shown that a large fraction of the gaseous component of colliding galaxies can be expelled. Part of this tidal debris might fall back, be dispersed throughout the intergalactic medium or recondense to form a new generation of galaxies: the so-called tidal dwarf galaxies. The latter are nearby examples of galaxies in formation. The properties of these recycled objects are reviewed here and different ways to identify them are reviewed.

### 1. Recycling the H I gas

The VLA and other synthesis arrays have, for twenty years and more, revealed the spectacular distribution of the atomic hydrogen (H I) in interacting systems. Long tidal tails that are even more prominent than their optical counterparts, bridges, and ring-like structures are among the many weird and wonderful features which show up in high resolution maps (see Schiminovich et al., this volume). Because in general the H I in disk galaxies extends well beyond the optical  $R_{25}$  radius, this atomic hydrogen reacts very efficiently to any external perturbation as evidenced by the fact that most of the neutral gas is found outside the colliding disks. In systems like Arp 105 and NGC 7252 (see Fig. 1), up to 90% of the gas visible at 21 cm is situated in the intergalactic medium (IGM) and little, if any gas remains within the parent spirals. In addition to gas being actively removed, a large part of the original H I has likely been funnelled inward where it was transformed into another phase (see review by Struck, 1999).

The fate of the tidally expelled gas will largely depend on its density and location with respect to the interacting galaxies. Whereas the clouds closest to the interacting (or merging) pair will fall back at timescales of a few Myr

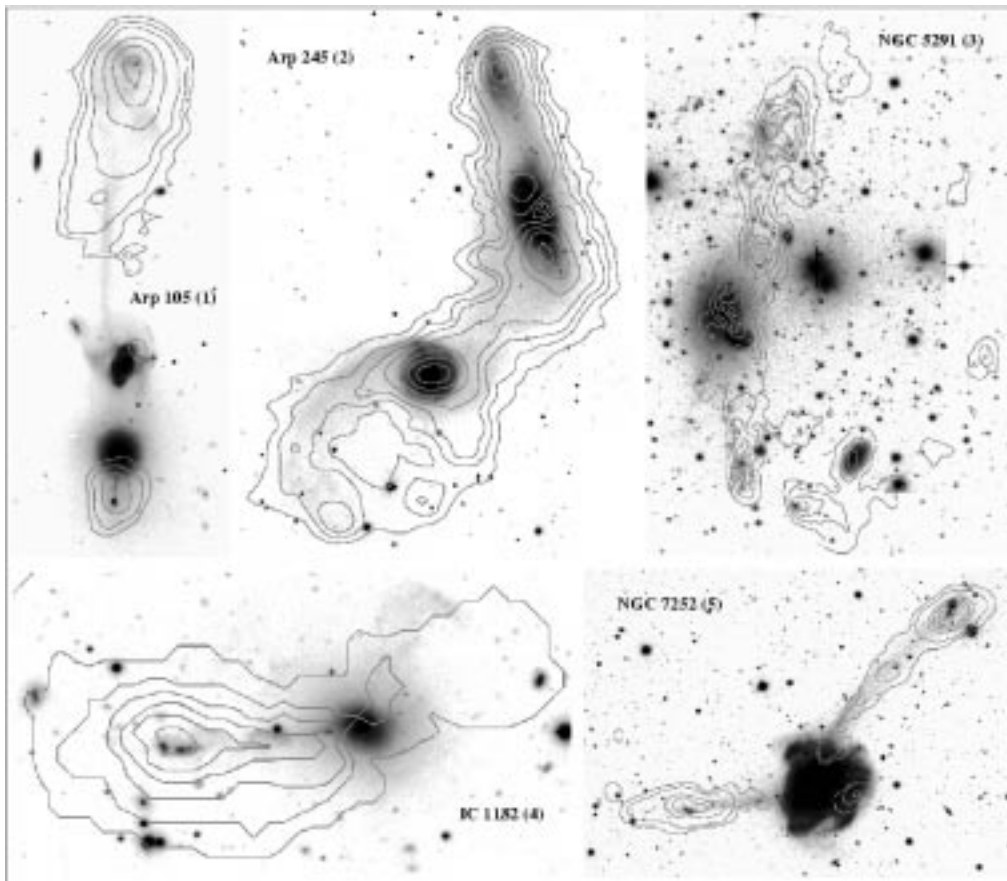


Figure 1. H I distributions for a sample of interacting systems which have formed some tidal dwarf galaxies. The H I contours are superimposed on optical V-band images; references for the H I VLA data: 1) Duc et al. (1997); 2) Duc et al. (2000); 3) Malphrus et al. (1997), and Duc & Mirabel (1998); 4) Dickey (1997); 5) Hibbard et al. (1994)

(Hibbard & Mihos, 1995), the most distant ones will become gravitationally unbound. They might slowly diffuse and enrich the IGM with heavy elements or the stars might even form the basis of the faint background light in the intracluster medium (ICM) if the interacting system belongs to a cluster. Under certain conditions, however, tidal debris may be recycled. If self-gravity is sufficiently large, expelled clouds will condense and collapse again to build new star-forming objects. Offspring as massive as magellanic dwarf irregular galaxies has been observed around several interacting systems (see for examples Fig. 1). Generally situated at the tip of 50–100 kpc long tidal tails, they are referred to as Tidal Dwarf Galaxies (TDGs). The total gas fraction that could end up in a TDG is yet largely unknown and it is hoped that numerical simulations might one day get a handle on this. Observationally, H I clouds towards TDGs as massive as  $5 \times 10^9 M_{\odot}$  have been measured.

## 2. Forming tidal dwarf galaxies

Not only H I clouds are expelled during tidal interactions, but any material that was originally (rotating) in a disk, in particular the stars. Therefore TDGs are mixed bags, composed of young stars formed *in situ* from collapsing gas clouds and an older population pulled out from their parent galaxies. The latter component may be unimportant in systems involving gas-rich early type galaxies (i.e. NGC 5291, Duc & Mirabel 1998; see also Fig. 1). Instabilities in the gaseous — H I — component seem to be the driving factor in the formation of TDGs. Star formation occurs at rates which might reach  $0.1 \text{ M}_{\odot} \text{ yr}^{-1}$ . Given that TDGs contain huge H I reservoirs, typically  $10^9 \text{ M}_{\odot}$ , it is to be expected that the relative importance of an older stellar population will decrease with time as SF proceeds. Appreciable quantities of molecular gas have also recently been detected in TDGs by Braine et al. (2000). They suggest that this gas has been formed *in situ* out of the collapsed H I.

## 3. Identifying tidal dwarf galaxies

Tidal objects will survive provided that they have a potential well that is deep enough to sustain themselves against internal or external disruption. When identifying TDGs, it is therefore important to check that they are not simply the agglomerated debris of a collision but are self-gravitating entities (Duc et al. 2000). One should hence try to distinguish those tidal features that are kinematically decoupled from their host tails, the kinematics of which is governed by streaming motions. Because of the difficulty of obtaining high sensitivity, high resolution H I data, and problems related to projection effects along the line of sight, this is a difficult task that requires a careful examination of the available datacubes, such as those provided by synthesis radio observations (for the neutral gas component), and Fabry-Perot or any integral field instrument (for the ionised component). Addressing the stellar kinematics would be even more challenging. So far, evidence for such self-gravitating clouds have been found in the interacting systems Arp 105 (Duc et al. 1997; see Fig. 2), NGC 5291 (Duc & Mirabel 1998) and perhaps Arp 245 (Duc et al. 2000).

It is one thing to pick out TDGs which are still linked to the tidal tails out of which they formed. But how can one recognise old tidal dwarf galaxies that would have lost their physical connection with their parent galaxies as the tidal tail linking it vanishes with time? One might make use of three special properties of TDGs. First of all, their metallicity: due to the fact that they are recycled material, it is much higher than that of classical dwarf galaxies of the same luminosity (Duc et al. 2000). The oxygen abundance of recently formed TDGs averages out at one third of solar, i.e., the abundance of spirals at or slightly beyond the optical  $R_{25}$  radius. Secondly, it is expected that TDGs contain little if any dark matter *if* DM in their progenitors was distributed in a large halo, as is traditionally assumed (Barnes & Hernquist, 1992). If however, DM is present in disks, for instance in the form of cold molecular gas (Pfenninger et al., this volume) DM dominated tidal tails should form and TDGs would have a substantial DM content. Finally, the stellar population of TDGs should at least be bimodal: a fraction of their stars has originally come from the parent

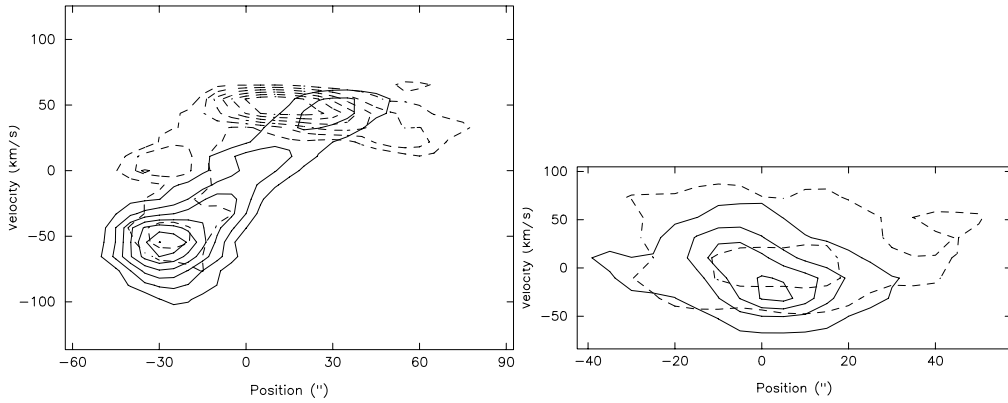


Figure 2. H I position-velocity diagrams towards the tidal tails of Arp 105 (left) and Arp 245 (right). Two components have been identified and disentangled using cuts made at different positions along the tails: one component is associated with gas following a streaming motion along the tail (dashed contours), and a second one which appears to be kinematically decoupled (full contours) and which coincides spatially with the optical tidal dwarf galaxy. Adapted from Duc et al. 1997, and Duc et al. 2000.

disks, whereas another part has been formed *in situ*. Reconstructing the star formation history of a galaxy using for instance its color-magnitude diagram might reveal a tidal origin. These methods have already been used to identify some older TDG candidates, both in the field as well as in clusters (Hunter et al. 2000; Duc et al., in prep). But so far, the overall fraction of dwarf galaxies of tidal origin remains unknown.

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